Calculations executed for the 3-bladed rotor of the VIRYA-1.02 windmill (λ_d = 3.5, 15° folded stainless steel blades) meant to be coupled to the VIRYA-1 generator

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Drawing VIRYA-1.02 rotor

1 Introduction

The 3-bladed VIRYA-1.02 is an alternative for the 2-bladed VIRYA-1. The rotor blades of the VIRYA-1 have a 7.14 % cambered airfoil. Cambering requires a special press. For twisting of the blades, special tools for cambered blades are needed. These tools are relatively expensive if only one windmill is built. In this report KD 678 it is investigated if it is possible to use rectangular blades with folded sides because now much simpler and cheaper tools are needed.

The VIRYA-1.02 makes use of the same 8-pole axial flux generator which is also used for the third version of the VIRYA-1 and which is described in report KD 679 (ref. 1). KD 679 includes drawings of the armature sheet, the stator sheet and the coils. This generator uses the front wheel hub of a mountain bike as generator housing.

The VIRYA-1.02 and the VIRYA-1 make use of the head, the tower pipe and the safety system of the 3-bladed VIRYA-1.04. The rotor calculations of the VIRYA-1.04 are given in report KD 518 (ref. 2). The drawings of the VIRYA-1.04 are given in a separate manual (ref. 3). This manual includes the drawings of the head. The VIRYA-1.04 makes use of a Nexus hub dynamo but the maximum power of this dynamo is only about 6 W for 12 V battery charging. The rotor diameter of the VIRYA-1.02 is chosen a little smaller than that of the VIRYA-1.04 to make an efficient use of the chosen materials. The rated wind speed is about 8 m/s for a 1.5 mm aluminium vane blade.

2 Description of the rotor of the VIRYA-1.02 windmill

The 3-bladed rotor of the VIRYA-1.02 windmill has a diameter D = 1.02 m and a design tip speed ratio λ_d = 3.5. Advantages of a 3-bladed rotor are that the gyroscopic moment in the rotor shaft is not fluctuating and that a 3-bladed rotor looks nicer than a 2-bladed rotor.

The rotor has three blades which are made of rectangular stainless steel sheets with size 125 * 416 * 1 mm. 60 blades can be made out of a standard sheet of 1.25 * 2.5 m with almost no waste material. All four corners of a blade are rounded with r = 5 mm. The blade has no camber but in stead of camber, both 27.5 mm wide sides are bent forwards over an angle of 15°. It is expected that the aerodynamic characteristics of this special airfoil are about the same as for a 7.14 % cambered airfoil. The chord c is a little smaller than the strip width because of the bent sides. Assume c = 123 mm = 0.123 m. A blade is twisted linear.

The blades are connected to the generator by a stainless steel hub plate made out of 1.5 mm sheet. The hub plate has three 120 mm long and 70 mm wide ears. The overlap in between an ear and a blade is 26 mm resulting in a rotor diameter of 1020 mm. A blade is connected to the hub plate by two stainless steel bolts M5 * 10, two self locking nuts M5 and two washers. The inner 30 mm of the hub plate is flat. The ear is twisted in between this flat side and the blade root to get the correct blade setting angle. The rotor mass is about 1.5 kg.

The aluminium front wheel hub of a mountain bike has two identical flanges. For connection of the spokes, each flange has 18, 2.6 mm holes at a pitch angle of 20° and at a pitch circle diameter of 45 mm. The hub plate is connected to the front flange and six 2.6 mm holes in this flange are enlarged up to 4 mm. The front flange has a collar with a diameter of 35 mm. A 35.2 mm central hole is made in the hub plate for centring on the collar. The hub plate is connected to the front flange by six stainless steel bolts M4 * 10, six self locking nuts M4 and six washers. The armature sheet of the generator is connected to the back flange and six 2.6 mm holes in this flange are enlarged up to 4 mm.

It is expected that it is not necessary to balance the rotor if the hole patterns in the blades and the hub plate are made accurately. However, if there is some imbalance, this can be corrected by grinding a little from the heaviest blade tip. The drawing of the rotor with drawing number 1902- 01 is given in appendix 1.

3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 4). This report (KD 678) has its own formula numbering. Substitution of $\lambda_d = 3.5$ and $R = 0.51$ m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 6.8627 * r \qquad (-) \qquad (1)$$

Formula's (5.2) and (5.3) of KD 35 stay the same so:

$$\beta = \phi - \alpha \qquad (°) \qquad (2)$$

$$\phi = 2/3 \arctan 1 / \lambda_{r\,d} \qquad (°) \qquad (3)$$

Substitution of $B = 3$ and $c = 0.123$ m in formula (5.4) of KD 35 gives:

$$C_l = 68.110\, r\, (1 - \cos\phi) \qquad (-) \qquad (4)$$

Substitution of $V = 5$ m/s and $c = 0.123$ m in formula (5.5) of KD 35 gives:

$$R_{e\,r} = 0.410 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)} \qquad (-) \qquad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.078 m. Station A corresponds to the blade tip. Station F corresponds to the end of a hub plate ear. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root. First the theoretical values are determined for C_l, α and β and next β is linearised such that the twist is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

Although the blade has 15° bent sides, it is assumed that the aerodynamic characteristics for 7.14 % camber can be used. Aerodynamic characteristics for 7.14 % camber are given in report KD 398 (ref. 5). The Reynolds values for the stations are calculated for a wind speed of 5 m/s because this is a reasonable wind speed for a windmill which is designed for a rated wind speed of 8 m/s.

sta-tion	r (m)	λ_{rd} (-)	ϕ (°)	c (m)	$C_{l\,th}$ (-)	$C_{l\,lin}$ (-)	$R_{e\,r} * 10^{-5}$ V = 5 m/s	$R_e * 10^{-5}$ 7.14 %	α_{th} (°)	α_{lin} (°)	β_{th} (°)	β_{lin} (°)	$C_d/C_{l\,lin}$ (-)
A	0.51	3.5	10.6	0.123	0.60	0.70	1.46	1.7	0.0	0.6	10.6	10	0.051
B	0.432	2.965	12.4	0.123	0.69	0.65	1.25	1.2	0.9	0.6	11.5	11.8	0.043
C	0.354	2.429	14.9	0.123	0.81	0.78	1.03	1.2	1.7	1.3	13.2	13.6	0.039
D	0.276	1.894	18.6	0.123	0.98	1.01	0.86	1.2	3.0	3.2	15.6	15.4	0.030
E	0.198	1.359	24.2	0.123	1.19	1.31	0.62	1.2	5.1	7.0	19.1	17.2	0.051
F	0.12	0.824	33.7	0.123	1.37	1.30	0.43	1.2	8.2	14.7	25.5	19	0.23

table 1 Calculation of the blade geometry of the VIRYA-1.02 rotor

The theoretical blade angle β_{th} varies in between 10.6° and 25.5°. If the blade angle is taken 10° at the blade tip and 19° at the blade root, the linearised blade angles are lying close to the theoretical values for the most important outer part of the blade. A hub plate ear is twisted 19° right hand in between the flat inner 30 mm and station F to get the correct blade angle at station F (the rotor is rotating right hand). A blade is twisted 9° left hand in between station A and station F to get a blade angle of 10° at the blade tip.

4 Determination of the C_p-λ and the C_q-λ curves

The determination of the C_p-λ and C_q-λ curves is given in chapter 6 of KD 35. The average C_d/C_l ratio for the outer part of the blade is about 0.04. However, as the used airfoil is not a 7.14 % cambered sheet but a flat sheet with 15° bevelled edges, a higher value of 0.07 is chosen. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 3.5$ and $C_d/C_l = 0.07$ gives $C_{p\ th} = 0.38$.
The blade is stalling at station F. So for the calculation op $C_{p\ max}$, not the real blade length k = 0.416 m is taken but only a length up to 0.04 m outside station F. This gives an effective blade length k’ = 0.35 m. Substitution of $C_{p\ th} = 0.38$, R = 0.51 m and k = k’ = 0.35 m in formula 6.3 of KD 35 gives $C_{p\ max} = 0.34$. $C_{q\ opt} = C_{p\ max} / \lambda_{opt} = 0.34 / 3.5 = 0.0971$.
Substitution of $\lambda_{opt} = \lambda_d = 3.5$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 5.6$.
The starting torque coefficient is calculated with formula 6.12 of KD 35 which is copied as formula 6.

$$C_{q\ start} = 0.75 * B * (R - \tfrac{1}{2}k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (6)$$

The average blade angle $\beta = 14.5°$. For a non rotating rotor, the angle $\phi = 90°$. The average angle of attack α is therefore 90° - 14.5° = 75.5°. The C_l-α curve for large angles α is given in figure 5 of report KD 398 for 10 % camber. It is assumed that this curve can also be used for a stalling airfoil with 15° folded sides. For $\alpha = 75.5°$ it can be read that $C_l = 0.49$. The whole airfoil is stalling at stand still position, so now the real blade length k = 0.416 m is taken.

Substitution of B = 3, R = 0.51 m, k = 0.416 m, $C_l = 0.49$ and c = 0.123 m in formula 6 gives that $C_{q\ start} = 0.041$. The real starting torque coefficient will be somewhat lower because the average blade angle was used. Assume $C_{q\ start} = 0.035$. For the ratio in between the starting torque and the optimum torque we find that it is 0.035 / 0.0971 = 0.36. This is rather high for a rotor with a design tip speed ratio of 3.5.

The starting wind speed V_{start} of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * \tfrac{1}{2}\rho * \pi R^3}\right)} \qquad (m/s) \qquad (7)$$

The sticking torque Q_s of the generator is very low at n = 0 rpm because it is only caused by the friction of the bearings. It is increasing slowly at increasing rotational speeds because of the eddy currents in the steel stator sheet. The unloaded Q-n curve has been measured and is given in figure 7 of KD 626. It is about 0.02 Nm at stand still position. Substitution of $Q_s = 0.02$ Nm, $C_{q\ start} = 0.035$, $\rho = 1.2$ kg/m^3 and R = 0.51 m in formula 7 gives that $V_{start} = 1.5$ m/s which is very low. The Q-n curve of the rotor will rise faster at low rotational speeds than the unloaded Q-n curve of the generator, so the rotor will really start at V = 1.5 m/s. A starting wind speed of 1.5 m/s is lower than for the VIRYA-1 rotor for which V_{start} is about 2 m/s. The starting wind speed of the VIRYA-1.04 is about 2.6 m/s, so a lot higher. So the starting behaviour of the VIRYA-1.02 will be very good and the VIRYA-1.02 can therefore be used in regions with low wind speeds.

The VIRYA-1.02 has a design tip speed ratio of 3.5 in stead of 4.25 and a rated wind speed of 8 m/s in stead 9 m/s for the VIRYA-1, so the maximum tip speed of the VIRYA-1.02 will be lower. But an airfoil with 15° folded sides may have more turbulence than a 7.14 % cambered sheet and therefore it is expected that the noise production is about equal.

In chapter 6.4 of KD 35 it is explained how rather accurate C_p-λ and C_q-λ curves can be determined if only two points of the C_p-λ curve and one point of the C_q-λ curve are known. The first part of the C_q-λ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for $\lambda = 0$.

Kragten Design developed a method with which the value of C_q for low values of λ can be determined (see report KD 97 ref. 6). With this method, it can be determined that the C_q-λ curve is directly rising for low values of λ if a 7.14 % cambered sheet airfoil is used. It is assumed that this is also true for the chosen airfoils with 15° folded sides. This effect has been taken into account and the estimated C_p-λ and C_q-λ curves for the VIRYA-1.02 rotor are given in figure 1 and 2.

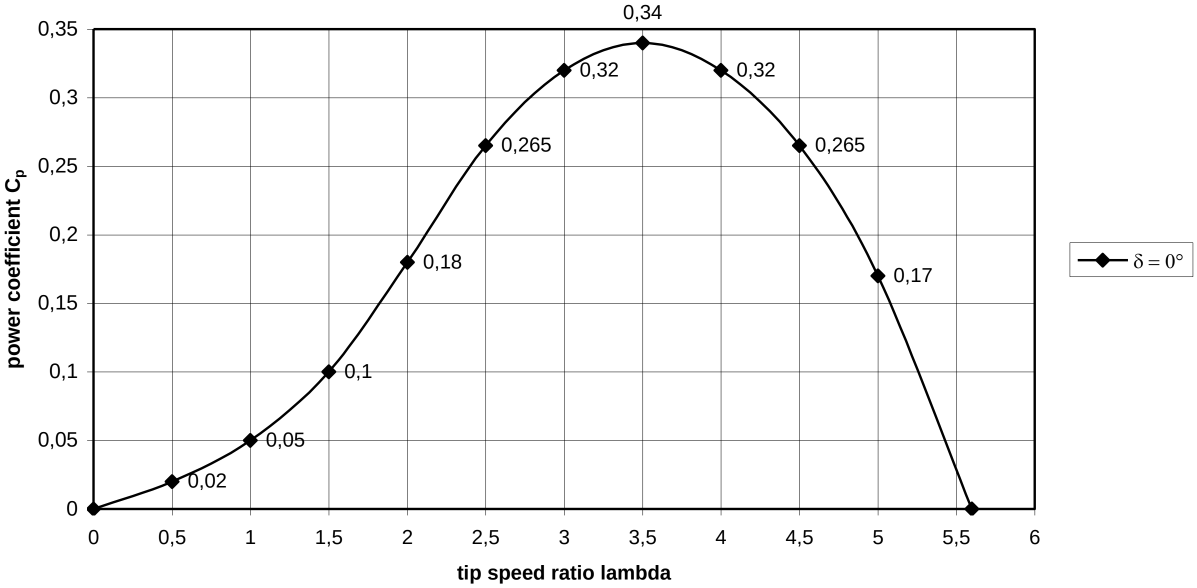

fig. 1 Estimated C_p-λ curve for the VIRYA-1.02 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

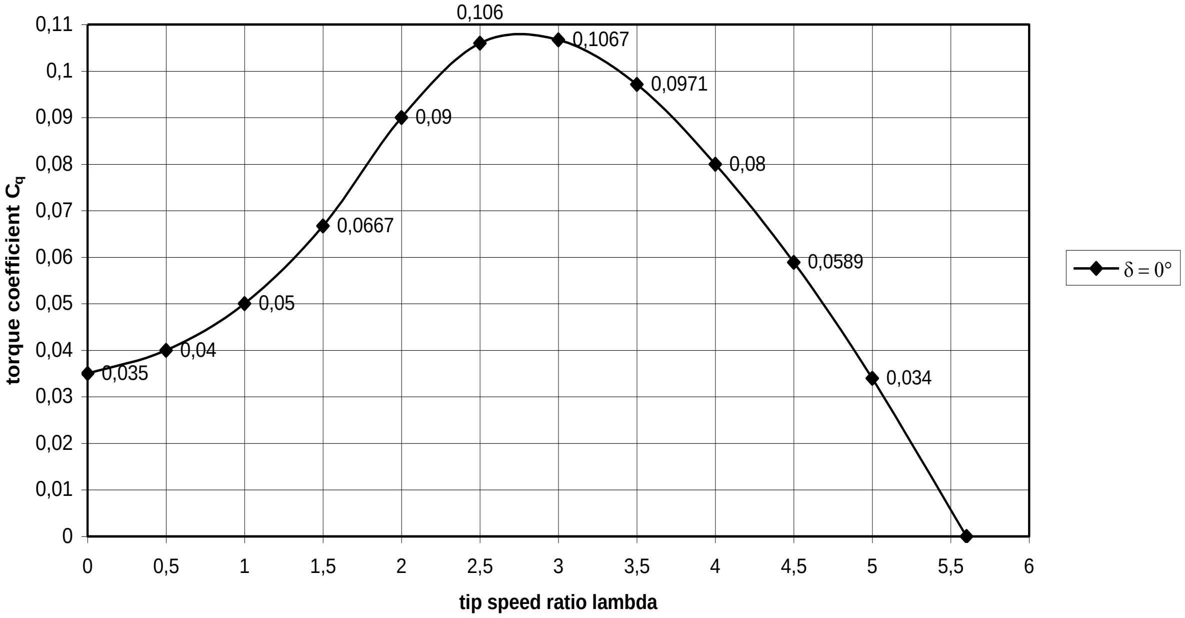

fig. 2 Estimated C_q-λ curve for the VIRYA-1.02 rotor for the wind direction perpendicular to the rotor ($\delta = 0°$)

5 Determination of the P-n curves, the optimum cubic line and the P_{el}-V curve

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a C_p-λ curve of the rotor and the δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The C_p-λ curve is given in figure 1. The δ-V curve for a 1.5 mm aluminium is estimated on the basis of the proven δ-V curves of the VIRYA-1.8 and 2.2S windmills which have a 1 mm stainless steel vane blade and which have a rated wind speed of about 11 m/s. The estimated δ-V curve for a 1.5 mm aluminium vane blade is given in figure 3.

The head starts to turn away at a wind speed of about 5 m/s. For wind speeds above 8 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 8 m/s will therefore also be valid for wind speeds higher than 8 m/s.

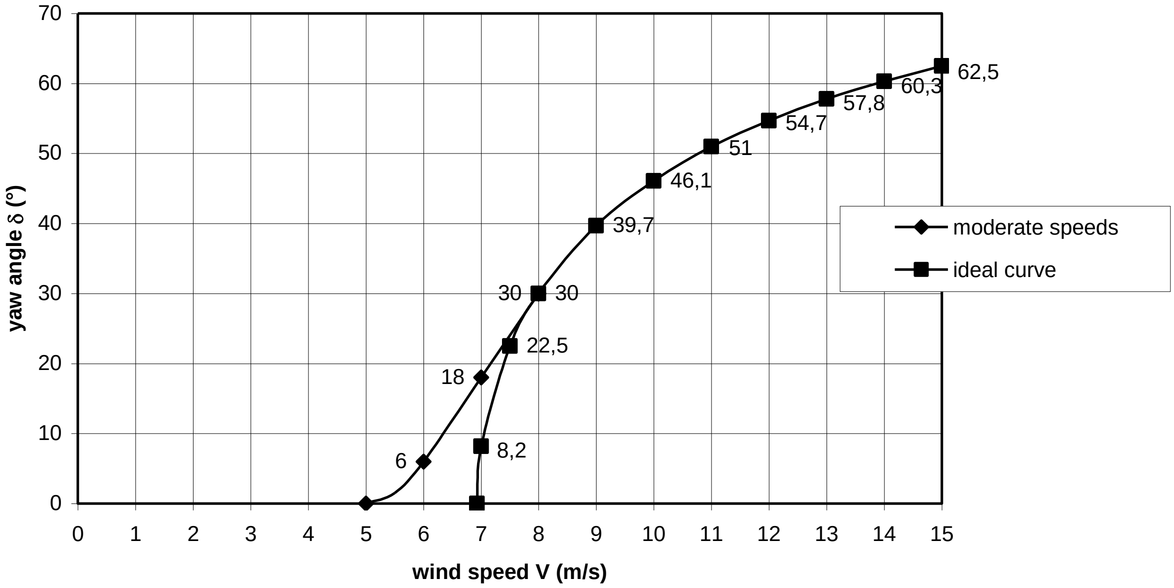

fig. 3 Estimated δ-V curve VIRYA-1.02 for a 1.5 mm aluminium vane blade

The P-n curves are used to check the matching with the P_{mech}-n curve of the generator for a certain gear ratio i (the VIRYA-1.02 has no gearing so i = 1). Because the P-n curve for low values of λ appears to lie very close to each other, the P-n curves are not determined for very low values of λ. The P-n curves are determined for C_p values belonging to λ is 2, 2.5, 3, 3.5, 4, 4.5, 5 and 5.6 (see figure 1). The P-n curves are determined for wind the speeds 2, 3, 4, 5, 6, 7 and 8 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 0.51 m in formula 7.1 of KD 35 gives:

$$n = 18.724 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of $\rho = 1.2$ kg / m^3 and R = 0.51 m in formula 7.10 of KD 35 gives:

$$P = 0.4903 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

For a certain wind speed, for instance V = 3 m/s, related values of C_p and λ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed.

		V = 2 m/s $\delta = 0°$		V = 3 m/s $\delta = 0°$		V = 4 m/s $\delta = 0°$		V = 5 m/s $\delta = 0°$		V = 6 m/s $\delta = 6°$		V = 7 m/s $\delta = 18°$		V = 8 m/s $\delta = 30°$	
λ	C_p	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n (rpm)	P (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)	n_δ (rpm)	P_δ (W)
2	0.18	74.9	0.71	112.3	2.38	149.8	5.65	187.2	11.03	223.5	18.75	249.3	26.04	259.4	29.35
2.5	0.265	93.6	1.04	140.4	3.51	187.2	8.32	234.1	16.24	279.3	27.61	311.6	38.34	324.3	43.21
3	0.32	112.3	1.26	168.5	4.24	224.7	10.04	280.9	19.61	335.2	33.34	374.0	46.29	389.2	52.18
3.5	0.34	131.1	1.33	196.6	4.50	262.1	10.67	327.7	20.84	391.0	35.42	436.3	49.19	454.0	55.44
4	0.32	149.8	1.26	224.7	4.24	299.6	10.04	374.5	19.61	446.9	33.34	498.6	46.29	518.9	52.18
4.5	0.265	168.5	1.04	252.8	3.51	337.0	8.32	421.3	16.24	502.8	27.61	560.9	38.34	583.8	43.21
5	0.17	187.2	0.67	280.9	2.25	374.5	5.33	468.1	10.42	558.6	17.71	623.3	24.59	648.6	27.72
5.6	0	209.7	0	314.6	0	419.4	0	524.3	0	625.7	0	698.1	0	726.5	0

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-1.02 rotor

The calculated values for n and P are plotted in figure 4. The optimum cubic line which is going through the tops of the P_{mech}-n curves is also given in figure 4.

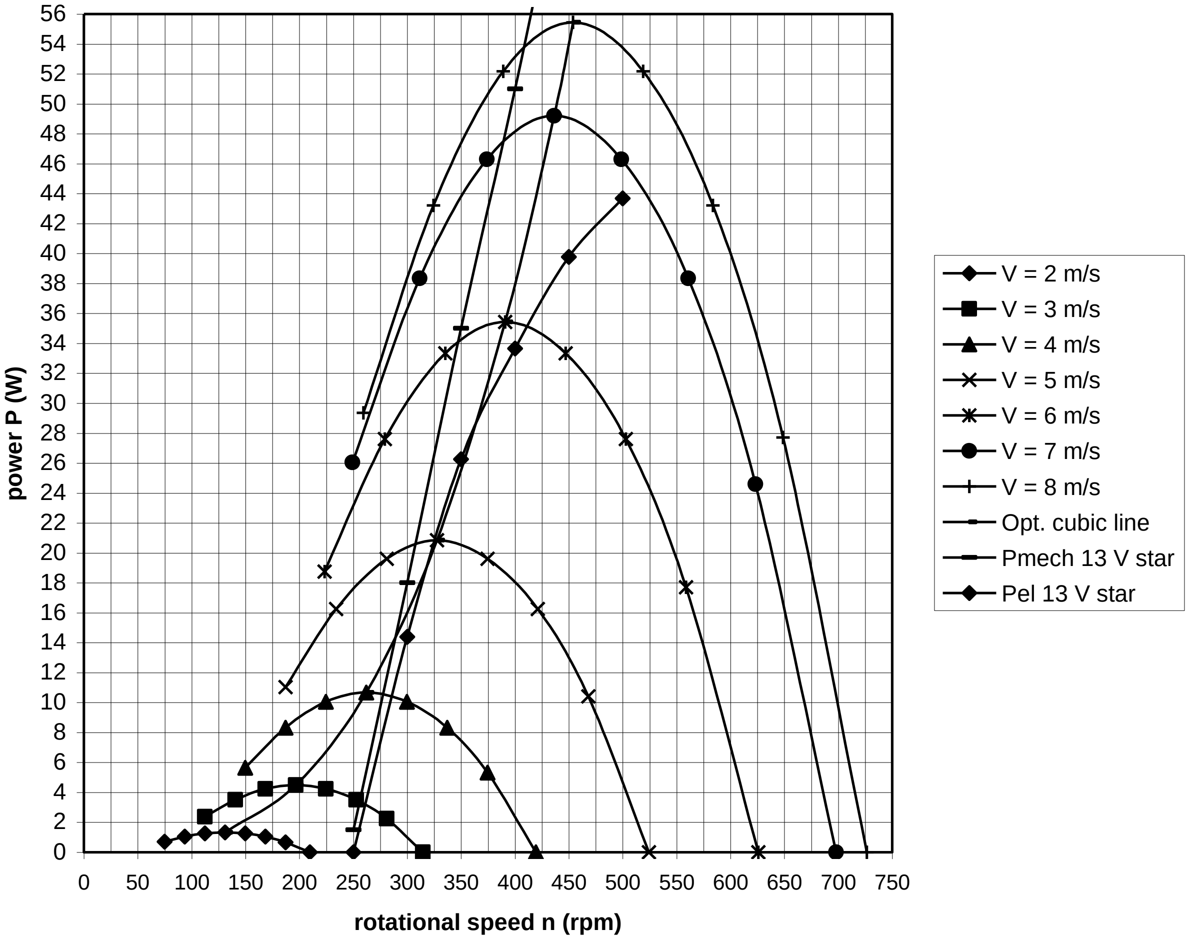

fig. 4 P-n curves and optimum cubic line of the VIRYA-1.02 rotor

A prototype of the generator has not yet been built, so measured characteristics of the generator for a 12 V battery load are not available. However, the P_{mech}-n and P_{el}-n curves for 13 V star are estimated and given in figure 5 of KD 626. These curves are copied in figure 4.

The working point for a certain wind speed is the point of intersection of the P_{mech}-n curve of the generator and the P-n curve of the rotor for that wind speed. The P_{mech}-n curve intersects with the optimum cubic line at a wind speed of about 4.4 m/s. So the matching is perfect for this wind speed.

The matching is good for wind speeds in between 3 m/s and 8 m/s because the working point is lying a bit to the right side of the optimum cubic line for wind speeds in between 3 m/s and 4.4 m/s and a bit to the left side of the optimum cubic line for wind speeds above 4.4 m/s.

The corresponding electrical power P_{el} for a certain working point is found by going down vertically from the working point up to the point of intersection with the P_{el}-n curve of the generator. This is done for all wind speeds and the values of P_{el} found this way are given in the P_{el}-V curve of figure 5.

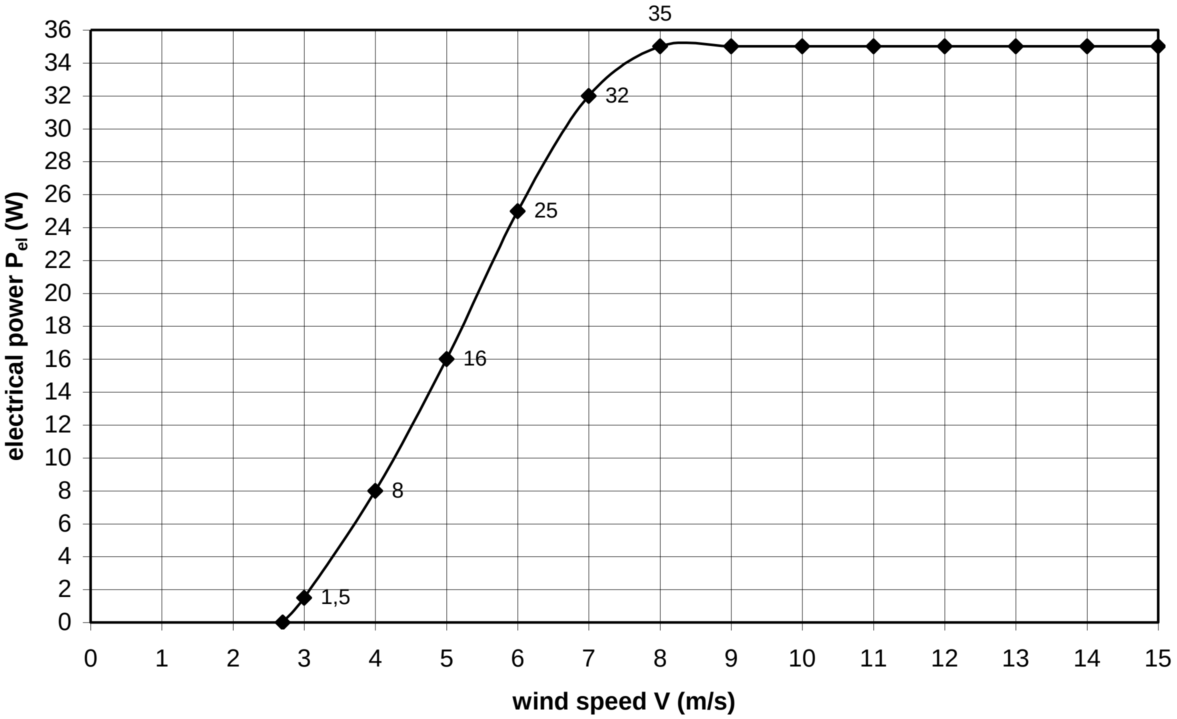

fig. 5 P_{el}-V curve of the VIRYA-1.02 windmill for 12 V battery charging

The wind speed where the generation of power starts is called the cut in wind speed $V_{cut\ in}$. In the P_{el}-V curve it can be seen that $V_{cut\ in}$ = 2.7 m/s. This is rather low. In chapter 4 it was calculated that the starting wind speed is 1.5 m/s. So there is no hysteresis in the P_{el}-V curve.

The maximum electrical power is about 35 W which is acceptable for a rotor with a diameter of 1.02 m and a rated wind speed of 8 m/s. However, the P_{el}-V curve is based on estimated P_{mech}-n and P_{el}-n curves. If a prototype of the generator is available, one should measure the generator for a 12 V battery load and check if the real curves are about the same as the estimated curves.

A maximum power of 35 W is that low that it is probably possible to use a large battery without a voltage controller and dump load which limits the maximum charging voltage if the battery is full.

The stainless steel hub plate ears are stronger than the aluminium blades of the VIRYA-1.04 rotor. Although the thickness of the blade is only 1 mm, it is stronger than a hub plate ear because the moment of resistance is increased a lot by the 15° bent sides. The strength of the VIRYA-1.04 rotor has been calculated in report KD 518 (ref. 7) and it was found that the VIRYA-1.04 rotor is strong enough. So the VIRYA-1.02 rotor will also be strong enough and separate calculations of the strength of the rotor will not be made.

6 Generator measurements

6.1 General

A prototype of the VIRYA-1.02 has been built by a teacher of a technical school in Rotterdam. This man wants to use this windmill for a project in Gambia for which the VIRYA-1.02 will be used to pump drinking water using a small 12 V electric pump. This use is described in report KD 672 (ref. 8) for the VIRYA-1 or the VIRYA-1.02 windmill.

Unfortunately the prototype of the VIRYA-1.02 generator wasn't made exactly according to the drawings which were valid at that time. It deviated at the following points:

A The stator sheet was made out of 3 mm galvanised steel sheet but the outer geometry wasn't made dodecagonal as it is specified on drawing 1703-01 of the VIRYA-1.25AF. It was made hexagonal as it is now specified on drawing 1604-02 of the VIRYA-1 which can be found in report KD 679 (ref. 1). The reason why I made the steel stator sheet dodecagonal was that I was afraid than a hexagonal sheet would get 24 preference positions per revolution. However, it appeared that a hexagonal sheet gives no preference positions (if stainless steel screws are used to connect the coils). So now it is decided to make the sheet hexagonal in stead of dodecagonal. The VIRYA-1.25AF with a dodecagonal stator sheet is cancelled, also because it appeared that the matching in between rotor and generator isn't good enough.

B The coil core is specified on drawing 1604-02 which can be found in report KD 679 (ref. 1). For the material it is specified polyacetal POM (Delrin, Ertacetal). However the coil cores were not made out of massive bar from this material but were made on a 3D printer and I don't know which material is used. For the original coil core, the front flange has a thickness of 1.3 mm and the back flange has a thickness of 0.7 mm. Both flanges have been made 1 mm for the prototype but this results in the same volume available for the coils. The coil winding has been made according to the specification so it is assumed that this modification has no influence of the generator characteristics.

C In stead of a front wheel hub of a mountain bike, a back wheel hub was used. This hub has a threaded part for connection of the chain sprocket and the shaft is much longer. Therefore it wasn't possible to connect the generator to the available hub of the test rig. So for the measurements, I have used the original front wheel hub with the original armature sheet and the original magnets but for the stator I have used the hexagonal stator sheet with six coils and the chosen 3-phase rectifier.

The test rig is described in report KD 595 (ref. 9) for use in combination with an axial flux generator of Hefei Top Grand. This test rig is provided with a chain transmission with a reducing gear ratio. Therefore generators can be measured with a rather large maximum torque level. However, the expected maximum torque level of the VIRYA-1 and the VIRYA-1.02 generator is rather low and the generator can therefore be mounted directly to the shaft of the driving motor. This shaft was provided with an aluminium bush and the front flange of the generator housing was connected to this bush by six screws M4. The base sheet of the test rig is clamped in the vice of my work bench.

This test rig has been used earlier to measure the unloaded torque Q as a function of the rotational speed n. These measurements are described in chapter 8 of report KD 679 (ref. 1).

The VIRYA-1.02 will be used to charge a 12 V lead acid battery with a capacity of about 60 Ah. However such a battery wasn't available. Therefore I have used a battery charge controller with a voltage controller which is adjusted at a voltage of about 13 V. This is about the average charging voltage of a 12 V battery. So the measured characteristics will deviate only slightly from the characteristics for a real 12 V battery.

For the determination of the P_{mech}-n, P_{el}-n and the η-n curves, one has to measure the torque Q, the rotational speed n, the DC voltage U and the DC current I. The rotational speed n has been measured with a laser rpm meter using a white dot on the hub of the driving motor. The voltage U and the current I have been measured with a digital universal meter.

As the generator hub is connected directly to the driving motor, the torque Q is the reaction torque needed to prevent that the stator sheet is rotating. The stator sheet is provided with a balanced lever with a length of the arm r = 0.141 m. An accurate analogue balance is placed on the floor below the vice of the work bench. This balance has a maximum range of 5 kg for five rotations of the pointer. The scale of the balance has a line every 5 gram and the pointer can be read with an accuracy of about 2 gram. The balance is loaded with a mass of 4.565 kg. A thin rope is connected in between the lever and this mass such that the torque Q results in a pulling force in the rope. So the pointer turns backwards at increasing torque. The pulling force F is proportional to the decrease of the measured mass Δm as shown by the pointer of the balance. The torque Q is given by:

$$Q = F * r \qquad (Nm) \tag{10}$$

In this formula, F is the force in the rope in N and r is the radius of the lever in m. However, a balance isn't measuring the force F in N but the mass m in kg. The relation in between F, Δm and the acceleration of gravity g (g = 9.81 m/s^2) is given by:

$$F = \Delta m * g \qquad (N) \tag{11}$$

(10) + (11) gives:

$$Q = \Delta m * g * r \qquad (Nm) \tag{12}$$

The mechanical power P_{mech} is given by:

$$P_{mech} = Q * \Omega \qquad (W) \tag{13}$$

In this formula, Q is the torque in Nm and Ω is the angular velocity in rad/s. The relation in between the angular velocity Ω (rad/s) and the rotational speed n (rpm) is given by:

$$\Omega = \pi * n / 30 \qquad (rad/s)` \tag{14}$$

(12) + (13) + (14) gives:

$$P_{mech} = \Delta m * g * r * \pi * n / 30 \qquad (W) \tag{15}$$

Substitution of g = 9.81 m/s^2, r = 0,141 m and π = 3,14159 in formula 15 gives:

$$P_{mech} = 0.1448 * \Delta m * n \qquad (W) \tag{16}$$

The supplied electrical power P_{el} is given by:

$$P_{el} = U * I \qquad (W) \tag{17}$$

In this formula U is the DC voltage and I is the DC current. So the losses in the rectifier are incorporated in the generator efficiency. The generator efficiency η in % is given by:

$$\eta = 100 * P_{el} / P_{mech} \qquad (\%) \tag{18}$$

6.2 Measuring results

First the unloaded DC voltage U was measured for rectification in star as a function of the rotational speed. The measured U-n curve is given in figure 6.

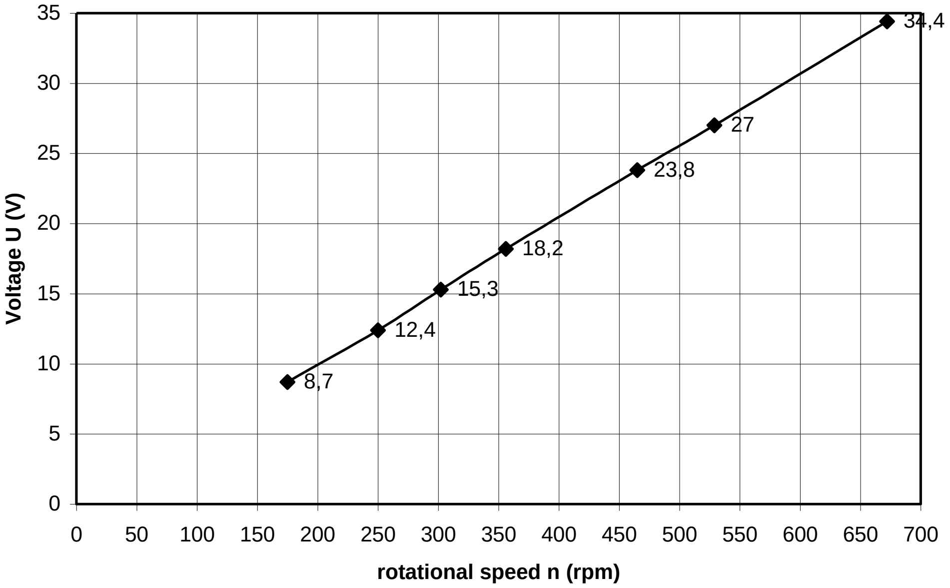

fig. 6 Open voltage U as a function of the rotational speed n for star rectification

In figure 6 it can be seen that the U-n curve is a straight line and that the open voltage U is 12.4 V at n = 250 rpm. The extended line is intersecting with the x-axis at about n = 10 rpm. In an earlier design report of the VIRYA-1 rotor it was determined that the winding of one coil should have 230 turns per coil for a wire thickness of 0.56 mm. It was expected that a complete winding with six coils would have an open voltage of 12.5 V at a rotational speed of 250 rpm if the winding is rectified in star. The measured open voltage is 12.4 V for n = 250 rpm, so the chosen number of turns per coil is correct.

Next the generator was measured, connected to a battery charge controller adjusted at a voltage of about 13 V. The measuring points and the calculated values for Q, P_{mech}, P_{el} and η are given in table 3. The η-n curve is given in figure 7.

n (rpm)	$m_{pointer}$ (kg)	Δm (kg)	Q (Nm)	P_{mech} (W)	U_{DC} (V)	I_{DC} (A)	P_{el} (W)	η (%)
157	4.545	0.020	0.028	0.45	6.8	0	0	-
250	4.535	0.030	0.041	1.09	12.2	0	0	-
273	4.525	0.040	0.055	1.58	13.05	0.02	0.26	16.5
290	4.495	0.070	0.097	2.94	13.13	0.10	1.31	44.6
305	4.455	0.110	0.152	4.94	13.14	0.19	2.50	51.5
320	4.427	0.138	0.191	6.39	13.15	0.27	3.55	55.6
359	4.333	0.232	0.321	12.06	13.15	0.53	6.97	57.8
390	4.261	0.304	0.420	17.17	13.16	0.73	9.61	56.0
431	4.166	0.399	0.552	24.90	13.16	0.98	12.90	51.8
479	4.053	0.512	0.708	35.51	13.17	1.32	17.38	48.9
515	3.970	0.595	0.823	44.37	13.18	1.58	20.82	46.9
564	3.870	0.695	0.961	56.76	13.18	1.86	25.51	44.9
601	3.790	0.775	1.072	67.44	13.18	2.20	29.00	43.0

Table 3 Measured and calculated values of the VIRYA-1.02 generator

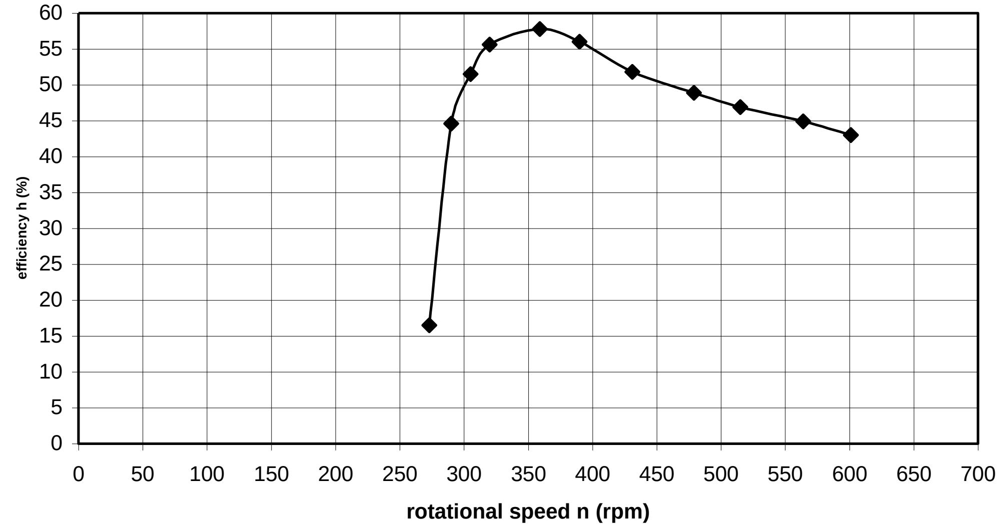

fig. 7 Measured η-n curve of the VIRYA-1.02 generator for 12 V battery charging.

Next figure 4 is copied as figure 8 but the estimated P_{mech}-n and P_{el}-n curves are replaced by the measured P_{mech}-n and P_{el}-n curves for 13 V star. A new P_{el}-V curve is derived using the measured P_{mech}-n and P_{el}-n curves and this new P_{el}-V curve is given in figure 9. For a real 12 V battery, the maximum charging voltage will be higher than 13 V at high powers resulting is a somewhat higher efficiency and a somewhat higher maximum power. The P_{el}-V curve is corrected for this effect at high wind speeds.

If the estimated and the measured P_{mech}-n and P_{el}-n curves are compared, it can be seen that the measured curves are lying a lot lower than the estimated curves. The rotor isn't running at the design tip speed ratio of 3.5 but at a tip speed ratio somewhat higher than 4 because the torque is lower than expected. But the matching is still acceptable.

The P_{mech}-n curve will shift to the left if a winding with more turns per coil is used. However, this will result in a longer and thinner wire and the copper losses will therefore increase and this results in decrease of the generator efficiency. I therefore think that the chosen and tested winding is still rather optimal for the VIRYA-1.02. The matching will be better for the 2-bladed VIRYA-1 rotor as this rotor has a design tip speed ratio of 4.25.

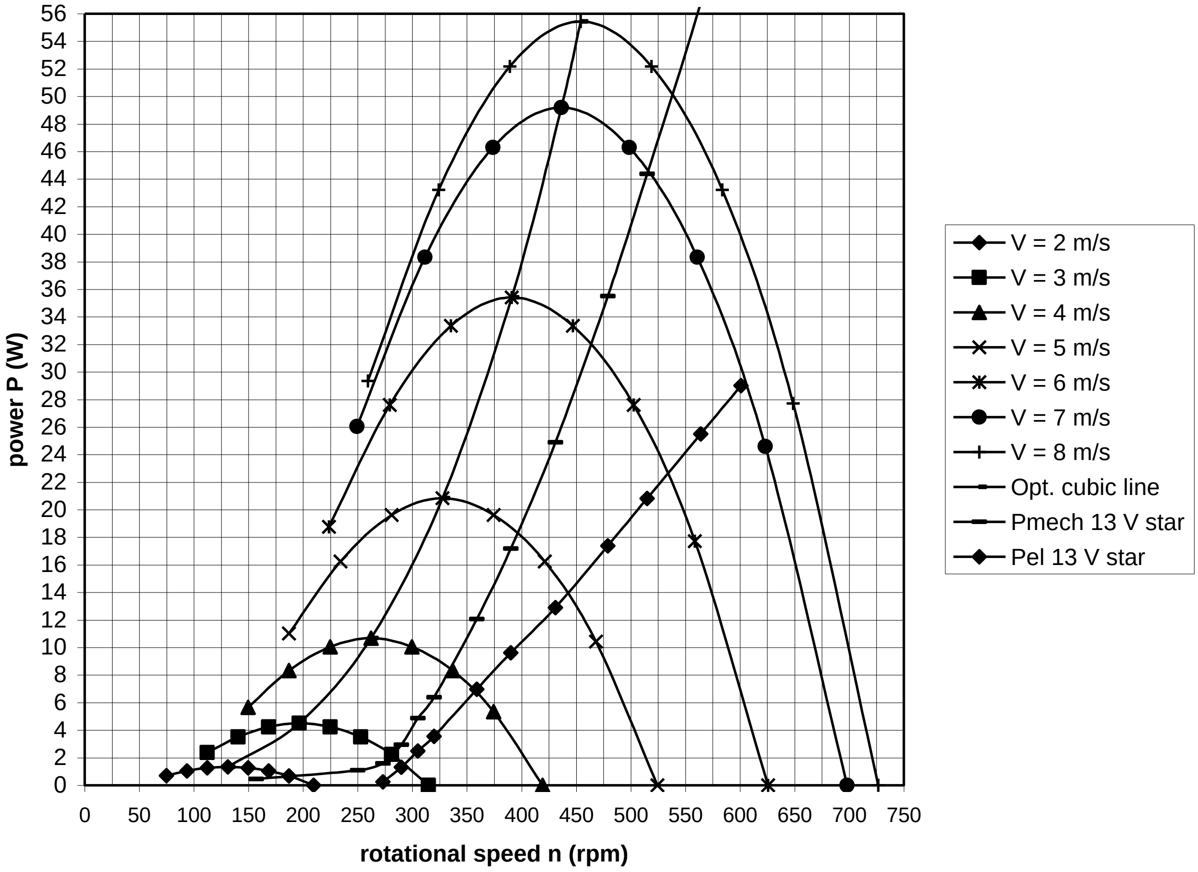

fig. 8 Estimated P-n curves and optimum cubic line of the VIRYA-1.02 rotor, measured P_{mech}-n and P_{el}-n curves.

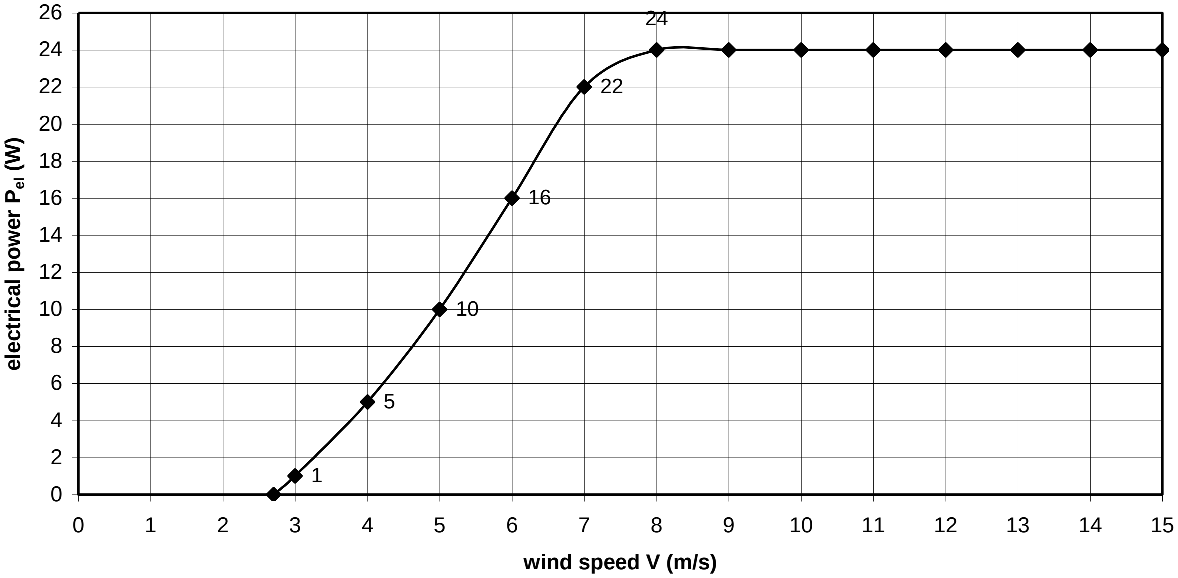

fig. 9 P_{el}-V curve of the VIRYA-1.02 for measured generator characteristics

The P_{el}-V curve is also lying lower than the estimated curve as given in figure 5 but for wind speeds above about 3.6 m/s, it is much better than the P_{el}-V curve of the VIRYA-1.04 with a Nexus hub dynamo (see figure 5 report KD 518, ref. 7).

7 References

1 Kragten A. Development of an 8-pole, 3-phase axial flux permanent magnet generator for the VIRYA-1 windmill using a bicycle hub and 8 neodymium magnets size ϕ 25 * 12 mm and a stator sheet made out of galvanised steel sheet, August 2019, free public report KD 679, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

2 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-1.04 windmill (λ_d = 3.5, 7.14 % cambered, aluminium blades) meant to be coupled to a Nexus hub dynamo (with free manual), January 2013, reviewed May 2013, free public report KD 518, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

3 Kragten A. Manual of electricity generating windmill VIRYA-1.04, February 2013, reviewed May 2013, free public manual, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

4 Kragten A. Rotor design and matching for horizontal axis wind turbines, July 1999, free public rapport KD 35, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

5 Kragten A. The 7.14 %, 10 % and 12.5 % cambered plate as airfoil for windmill rotor blades, Aerodynamic characteristics, geometry, moment of inertia I and moment of resistance W, November 2008, free public report KD 398, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

6 Kragten A. Determination of C_q for low values of λ. Deriving the C_p-λ and C_q-λ curves of the VIRYA-1.02.8D rotor, July 2002, free public report KD 97, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

7 Kragten A. Calculations executed for the 3-bladed rotor of the VIRYA-1.04 windmill (λ_d = 3.5, 7.14 % cambered aluminium blades) meant to be coupled to a Nexus hub dynamo. January 2013, reviewed May 2013, free public report KD 518, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

8 Kragten A. Use of the VIRYA-1 or the VIRYA-1.02 for pumping of drinking water using a 12 V battery and a pump with a 12 V DC motor. May 2019, reviewed August 2019, free public report KD 672, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

9 Kragten A. Measurements performed on a Chinese axial flux generator of Hefei Top Grand model TGET165-0.15 kW-500R for a 12 V battery load. September 2015, free public report KD 595, engineering office Kragten Design, Populierenlaan 51, 5492 SG Sint-Oedenrode, The Netherlands.

Appendix 1 Drawing VIRYA-1.02 rotor, $\lambda_d = 3.5$, $B = 3$